FINDINGS OF THE FIRST COMPREHENSIVE RADIOLOGICAL MONITORING PROGRAM OF THE REPUBLIC OF THE MARSHALL ISLANDS

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Abstract—**The Marshall Islands was the primary site of the United States atomic weapons testing program in the Pacific. From 1946 through 1958, 66 atomic weapons were detonated in the island country. For several decades, monitoring was conducted by the U.S. Department of Energy (or its predecessor agencies) on the test site atolls and neighboring atolls. However, 70% of the land area of the over 1,200 islands in the Marshall Islands was never systematically monitored prior to 1990. For the 5-y period from 1990 through 1994, the Government of the Republic of the Marshall Islands undertook an independent program to assess the radiological conditions throughout its 29 atolls. The scientific work was performed under the auspices of the Section 177 Agreement of the Compact of Free Association, U.S. public law 99-239, signed in 1986 by President Ronald Reagan. Although the total land area of the nations is a scant 180 km^2, the islands are distributed over 6 × 10^5 km^2 of ocean. Consequently, logistics and instrumentation were main considerations, in addition to cultural and language issues. The core of the monitoring program was *in-situ* gamma spectrometry measurements made on more than 400 islands. Native foods including coconuts and other tropical fruits were sampled as well as more than 200 soil profiles and more than 800 surface soil samples. The fruits, soil profiles and surface soil samples have been analyzed for all gamma emitters with an emphasis on determining concentrations of ^{137}Cs; the surface soil samples were also analyzed for $^{239+240}$Pu. All measurements were conducted in a radiological laboratory built in the capital city of the Marshall Islands specifically for the purposes of this study. The program was extensively assisted in the field and in the laboratory by Marshallese workers. The interpretation of environmental radiation data in the Marshall Islands required thoughtful analysis because the atolls lie along a latitude and precipitation gradient that effected the deposition of local and global fallout. The objective of this paper is to report findings for all atolls of the Marshall Islands on the ^{137}Cs areal inventory (Bq m^{-2}) and the external effective dose-rate (mSv y^{-1}), the projected internal effective dose-rate (mSv y^{-1}) from an assumed diet model, and surface soil concentrations of ^{239,240}Pu (Bq kg^{-1}) for selected northern atolls. Interpretation is also provided on the degree of contamination above global fallout levels. This report provides the first comprehensive summary of the radiological conditions throughout the Marshall Islands.**

Health Phys. 73(1):66–85; 1997

Key words: Marshall Islands; atomic bomb; fallout; ^{137}Cs

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(*Manuscript received* 31 *January* 1996; *revised manuscript received* 16 *October* 1996, *accepted* 7 *March* 1997)

0017-9078/97/$3.00/0

INTRODUCTION

THE U.S. Atomic Testing Program in the Pacific was conducted from 1946 through 1958 almost entirely in the Marshall Islands. Though various monitoring programs of the test site atolls and the atolls near the test sites have been conducted during the 50 y since the testing program began, the entire Marshall Islands had not been systematically monitored for residual radioactivity prior to 1990. For the 5-y period 1990 through 1994, the Republic of the Marshall Islands (RMI) Government undertook a radiological study of its 29 atolls to assess the radiological conditions at locations nationwide. The scientific work was performed as conceived by the Section 177 Agreement of the Compact of Free Association (COFA), an agreement between the former Trust Territory of the Pacific (now the RMI) and the United States (P.L. 99-239, 1986). The COFA, which provided the RMI with compensation for damages resulting from the U.S. Atomic Weapons Testing Program in the Pacific, specified the sum of $3 million to be used for radiological monitoring activities and medical surveillance. The purpose of this report is to present findings from the first comprehensive radiological monitoring program of the entire Marshall Islands.

In February of 1988, the Nitijela (Marshallese parliament) of the RMI adopted Resolution No. 3, which requested that the Cabinet of the RMI contract with scientists to investigate the levels of residual radiation in the Marshall Islands. The Nuclear Claims Tribunal§ undertook an international search for a suitable director scientist and a group of advisor scientists. In late 1989, a principal resident scientist (S.L.S.) was hired and an

§ The Nuclear Claims Tribunal is a judicial body appointed by the Nitijela whose purpose is to weigh evidence and provide financial awards for damages from the atomic testing program.

advisory group of non-US scientists was chosen (see McEwan et al. 1997 for a report of the activities of that advisory group).

Through the Section 177 Agreement of the COFA, the authors of the Compact ensured that the RMI would have the opportunity to conduct a monitoring program of its own design and with consideration of issues important to their nation. Though the technical design of the radiological monitoring program was a product of the primary author and the Scientific Advisory Panel, various leaders of the Marshall Islands government had input into the administration of the project. Thus, through a cooperative effort between leaders of the RMI Government, the resident scientist and advisors of varied expertise, an independent study was conducted with complete geographic coverage of the nation.

Historical context

Atomic weapons testing in the Marshall Islands was conducted by the United States during the years 1946 through 1958 at Bikini and Enewetak Atolls in the northwest corner of the archipelago. The early years of the testing program, 1946 through 1951, were relatively inactive (see Simon and Robison 1997). The total explosive yield of the Marshall Islands testing program was reported to be 1.07×10^8 tons TNT (U.S. DOE 1994): 71.8% of the yield was from the tests at Bikini Atoll and 28.2% was from those at Enewetak Atoll.

Bikini was the site of 24 tests including the first two atomic explosions following the end of WWII (Operations Crossroads, shots ABLE and BAKER). Bikini was also the site of the largest test the U.S. ever conducted: CASTLE BRAVO (15 MT explosive yield). That particular test caused the most severe consequences of any of the tests as a result of the exposure of Marshallese on several atolls downwind and due to the contamination of land outside the test site atoll. Enewetak Atoll was the site of 42 tests.

The people of Bikini and Enewetak were moved to other locations before the onset of testing on their home atolls. Up to the present time, neither group of people has ever recovered the full use of their lands though the communities are in various stages of rebuilding infrastructure and facilities for residence and industry. The era of atomic weapons testing in the Marshall Islands left a chronicle of technical data as well as social disruption, misunderstanding about radiation, and, for the Bikini and Enewetak people, several decades of displacement. The history of the movement of the Bikini people is described by Niedenthal (1997).

Radiological monitoring of the test site atolls and a number of other limited locations was conducted numerous times during and after the testing program. These various surveys were mainly conducted by the Atomic Energy Commission (AEC) and its successor agencies, the Energy Research and Development Administration (ERDA), and later the Department of Energy (DOE) or its contractor laboratories. In particular, the AEC Health and Safety Laboratory (HASL) conducted aerial gamma surveys of the atolls immediately following the tests of the IVY (Eisenbad 1953) and CASTLE (Breslin and Cassidy 1955) series. HASL also accumulated data on ground contamination by a network of fixed gamma measurement instruments at many atolls. In addition, one station of the HASL worldwide gummed film monitoring network was located at Kwajalein Atoll in the Marshall Islands. In addition to monitoring Rongelap Atoll in 1957, the AEC also monitored and cleaned Bikini to Department of Defense and AEC specifications in 1969. ERDA again monitored Bikini in 1957 and Brookhaven National Laboratory conducted an external radiation survey of five northern atolls in 1976. A large scale cleanup program of Enewetak was conducted by the Defense Nuclear Agency (DNA) in 1978–1980; the DNA program included a large laboratory and *in-situ* monitoring program. In 1978 the DOE contracted an aerial survey and ground sampling program of eleven northern atolls and two islands using the services of EG&G Energy Measurements Group, Lawrence Livermore National Laboratory and Brookhaven National Laboratory. The latter survey covered about 30% of the nation's area. Of these various monitoring programs, the aerial measurements conducted by HASL had the widest geographic coverage though the Northern Atoll Radiological Survey of 1978 was conducted with the highest level of spatial resolution. However, the Marshall Islands nation was not systematically monitored in its entirety until the implementation of the RMI Nationwide Radiological Study.

Data from a nationwide monitoring program were seen as potentially useful to a compensation program under design by the Nuclear Claims Tribunal. Thus, the Nationwide Radiological Study was designed and implemented to provide radiological monitoring of the complete geographic area of the chain of atolls that forms the RMI as well as to provide interpretation concerning possible radiation effects on human health and the environment (Simon et al. 1993).

The Nationwide Radiological Study (NWRS) was designed to fulfill the following goals:

1. To establish the geographic extent of fallout radioactivity throughout the RMI and to determine the present and future levels of radioactivity. Where possible, the past levels were to be determined;
2. To reassess the radiological conditions of Bikini, Enewetak, Rongelap and Utrik Atolls;
3. To provide advice to the RMI Government and to the Nuclear Claims Tribunal on (i) effects likely to be associated with the derived radiation exposure levels, (ii) health conditions related to radiation exposure, and (iii) to assist in the determination of exposure and risk to individuals where appropriate or possible; and
4. To provide information to the public of the Marshall Islands which explain and clarify the findings and to participate in educational activities concerning radiation and radioactivity and its potential health and environmental effects.

MATERIALS AND METHODS

Study design

During the planning phases of this study, numerous options were explored to determine the most appropriate and cost-effective technology for conducting a radiological monitoring program. Various technologies were considered, including an aerial survey with large volume scintillator detectors. However, because of the limited budget of the study and the remoteness of the Marshall Islands, the use of helicopters or fixed-wing aircraft was viewed as excessively expensive. Other factors were considered, including the simultaneous need to construct a laboratory to support the staff and perform radioactivity measurements on food and soil samples. Ground-level *in-situ* gamma spectrometry was determined to be most appropriate method in terms of providing useful data, minimizing expense, minimizing fear among the indigenous population—as can occur with aerial surveys—and providing an opportunity to employ Marshallese to assist in the monitoring program. These attributes were viewed as significant and important advantages over other methods.

A laboratory was designed and built in Majuro, the capital of the Marshall Islands. The laboratory office building provided facilities for drying fruit, tissue, and soil samples, crushing and grinding soil, storing samples, and performing wet chemistry including the extraction of plutonium from soil. The laboratory also contained facilities for gamma and alpha spectrometry as well as office space for staff. This laboratory became the first Marshall Islands Government institution of its type.

Sampling design considered sampling location within each atoll and sample size (i.e., the number of *in-situ* gamma spectrometry measurements per atoll). Islands greater than approximately 500 m in length in all atolls received at least a single measurement. The choice of sampling locations on each island was normally made during the course of the radiological survey by first evaluating visual cues and other environmental evidence to locate areas on each island with the least amount of natural or artificial disturbance. Within these areas, sampling locations were chosen at random except where necessary to maintain a minimum distance of about 30 m from the shoreline or manmade structures.

The interpretation of *in-situ* spectrometry data from situations with aged fallout is generally based on the exponential model to describe the vertical radioactivity distribution in the soil column (Beck et al. 1972). Many locations with aged fallout and without historical disturbance have been documented to show an exponential decline of radioactivity with increasing depth. Publications specific to the Marshall Islands have discussed the variation in relaxation length; typical values reported range from 7 cm to 15 cm (EG&G 1982; Graham and Simon 1996).

The number of *in-situ* gamma spectrometry measurements (sample size per atoll) was determined by considerations of resource allocation as well as expressions of the government or the local populace for information of high detail such as might be needed for evaluation of claims of land damage or to design remediation programs. At the atolls of the southern Marshall Islands, the sample size for *in-situ* gamma measurements was determined by the total counting time available during a single survey mission. Atoll surveys depended on logistical support from an ocean going vessel. The types of support necessary included transportation to and from the atoll, transportation between islands, providing food, drinking water, shelter, electricity for recharging instruments, and cargo space for carrying supplies of liquid nitrogen for HPGe detectors and for samples collected during the trip. Typically, ship support for the survey of a single atoll was restricted to a maximum of 10 d with 7 d as typical because of the limitations for carrying fuel and freshwater. *In-situ* counting time during the survey of a single atoll was generally limited to 2 h per measurement. Counting times of that length would allow two teams (three to five members each) to conduct up to sixty measurements during a week-long survey.

At atolls where historical data indicated significant contamination, public and government interest was generally greater. At these atolls, systematic sampling was used to ensure uniform geographic coverage of the islands. Square grids on 200-m centers were measured by compass and tape; *in-situ* measurement sites were chosen near to the center point of each grid square except as necessary to avoid shorelines, disturbed areas or manmade structures. The overall average spatial density of *in-situ* gamma spectrometry measurements in the NWRS was 10 per km^2 (see Table 1).

Description of samples

Samples of several different types were obtained to provide supplementary data to assist in the calibration of *in-situ* spectrometry instruments and also to provide necessary data for assessment calculations. Sample analysis was also necessary to answer questions from the local population concerning radioactivity in the environment and possible food contamination. At some locations, measurements with a high pressurized argon gas ionization chamber and electrometer were made to acquire data on the total gamma exposure-rate. Ionization chamber measurements were not made routinely because of manpower limitations. Every sampling location, however, was characterized by an *in-situ* gamma measurement with a counting time sufficiently long to ensure that the statistical counting error at one sigma confidence level be not greater than $\pm$ 10%. Standard geometry was maintained with a 1-m high downward facing crystal.

Surface soil samples were also obtained at many measurement sites for the purpose of laboratory analysis of transuranic radionuclides as well as for corroborative measurements of gamma emitting nuclides. Three surface soil samples, each 15 cm $\times$ 15 cm $\times$ 5 cm, were obtained at random locations within 15 m of the HPGe detector. The three subsamples were pooled to form a composite surface soil sample that was intended to be representative of the location of each *in-situ* gamma measurement.

Table 1. Summary data of monitoring program.

Atoll or island	Number of islands monitored in each atoll	Number of profiles per km^2	Number of *in-situ* measurements per km^2	Number of *in-situ* measurements per profile	Max/Min soil ^{137}Cs	Ratio of observed ^{137}Cs to global fallout estimates
Jabat Island	1	1.8	3.5	2.0	1.1	1.0
Knox	4	1.0	4.0	4.0	5.2	1.0
Lib Island	1	2.2	5.4	2.4	5.4	1.0
Namorik	2	0.7	2.5	3.5	2.5	1.0
Arno	20	0.3	2.4	7.7	50.9	1.1–2.1
Ebon	9	0.5	3.6	7.0	9.7	1.0–1.2
Ujae	6	1.6	6.8	4.3	32.4	1.0–1.3
Kili Island	1	0.5	4.3	8.3	8.0	1.0–1.4
Majuro	8	1.2	4.8	4.0	15.4	1.0–1.4
Ailinglaplap	21	0.3	2.5	9.1	16.6	1.0–1.5
Aur	10	0.5	3.0	5.7	3.4	1.0–1.6
Maloelap	16	0.4	2.8	6.7	13.6	1.0–1.8
Namu	16	0.6	6.8	10.7	6.3	1.0–1.8
Kwajalein	48	0.6	5.2	9.5	34.6	1.0–4.3
Jaluit	21	0.4	3.2	9.1	25.0	1.0–10.7
Lae	5	2.1	6.7	3.2	7.5	1.1–2.1
Mili	18	0.3	2.2	8.0	66.9	1.1–2.1
Taongi	6	0.9	5.0	5.4	6.8	1.1–2.1
Erikub	6	1.3	4.7	3.6	3.2	1.3–2.6
Bikar	3	2.0	10.0	5.0	2.3	1.4–2.7
Wotho	7	0.7	4.0	5.7	4.7	1.5–3.0
Ujelang	13	3.5	21.2	6.1	16.0	1.7–3.4
Wotje	21	0.5	3.3	6.7	3.4	1.9–3.8
Jemo Island	1	6.2	25.0	4.0	1.6	2.1–4.2
Likiep	25	0.6	5.3	9.2	9.7	3.9–7.7
Taka	4	7.0	17.5	2.5	24.6	4.8–9.7
Mejit Island	1	0.6	7.1	11.5	22.3	4.9–9.8
Ailuk	20	0.6	7.0	12.6	10.0	5.3–11.0
Utrik	4	1.6	20.4	12.8	6.8	11.0–21.0
Ailinginae	19	4.3	22.9	5.3	130.0	33.0–66.0
Rongerik	8	5.4	23.5	4.4	190.0	99.0–200.0
Rongelap	41	5.3	35.6	6.7	2900.0	140.0–1530.0
Enewetak	31	2.6	28.5	11.0	34100.0	200.0–1300.0
Bikini	15	2.8	16.5	5.9	3900.0	820.0–1650.0
Total	432	n/a[a]	n/a	n/a	n/a	n/a
Mean	12.7	1.8	9.6	6.6	1224.6	n/a
Median	8.5	1.0	5.3	6.0	9.9	n/a

[a] n/a = not applicable.

Soil profiles sampled in 5-cm increments to a total depth of 30 cm were also an important part of the sampling and measurement program. Characterization of the vertical profile of ^{137}Cs activity is a parameter of considerable importance to estimating the areal inventory. Over 200 soil profiles were acquired during the survey of the Marshall Islands. Generally a ratio of 1 soil profile to each 6 *in-situ* gamma measurements was maintained. Acquisition of all soil samples in the NWRS was by non-mechanized means except in a few instances when the NWRS was participating in intercomparison exercises with DOE contractors (limited to Bikini and Rongelap Atoll). Soil was carefully excavated by hand from the sides of a hand dug pit and taken to the laboratory in Majuro for processing and analysis. Further details of the soil profile sampling methodology and the findings are presented in Graham and Simon (1996).

Samples of locally grown food products were obtained in limited numbers to assist in the determination of the radiological conditions of the atolls. Generally plant concentrations for a single radionuclide (e.g., ^{137}Cs) are proportional to the specific activity of the radionuclide in the soil within the root zone of the plant. However, significant variations in uptake even at a single atoll are often observed due to local variations of both the contamination and soil characteristics such as drainage, composition, particle size, organic matter, stable element content, past salt intrusion, disturbance, etc., as well as the health and age of the plants.

There are also substantial variations in plant:soil ratios among different plant species. The most commonly used food plant in the Marshallese culture and the most common type of tree is the coconut palm (*Cocos nucifera*). Coconuts are used at many different stages of growth and in a variety of prepared foods. The clear liquid of the young coconut is an important source of fluid replenishment for Marshallese. Thus, coconuts, mainly of the young drinking stage, were sampled at all atolls. The sample size for coconuts was not uniform among the atolls due to manpower and time constraints during each survey. The liquid of the young coconuts (*ni*, pronounced as "nee" by Marshallese) was emptied into sampling bottles in the field; the soft meat of these coconuts (*mede* or "mé-dee" in Marshallese) was scooped out and stored in plastic containers for return to the laboratory.

Other sample types were obtained during the NWRS though sample size was not equal among the atolls. These sample types included breadfruit (*Artocarpus altilis*), Pandanus (*Pandanus spp.*), arrowroot (*Tacca leontopetaloides*), lime (*Citrus aurantifolia*), coconut crabs (*Birgus latro*) and meat of the giant clam (*Tridacna* clam). An ancillary study was made of the ^{137}Cs concentrations in plants used in traditional Marshallese medicine. The methodology and findings of that study were reported by Duffy (1993).

Instrumentation and laboratory methodology

Sample preparation and analysis were conducted according to laboratory protocols established during the initial phases of the project. All fruit, animal, and soil samples were dried to near 99%. Soils were crushed and ground to a particle size of less than 1.3 mm and thoroughly mixed in a rotating ball mill.

Laboratory precision and quality control was established by implementing several programs including the use of radioactivity standards traceable to NIST, repetitive measurements, use of internal tracers for plutonium analysis, participation in international intercomparisons conducted by the IAEA Laboratory in Monaco, and by conducting an in-house blind measurement intercomparison program with four international laboratories: Lawrence Livermore National Laboratory (Livermore, CA), the GSF Institut for Strahlenschutz (Munich, Germany), the National Radiation Laboratory of New Zealand (Christchuch, NZ) and Colorado State University (Ft. Collins, CO). One gauge of the level of agreement was the ratio of measurements obtained by the RMI laboratory to that of another participating institution. For example, in a comparison with LLNL, the ratios for ^{137}Cs in coconut fluid, coconut meat and soil were 0.94 ± 0.06 (1 SD, $n = 12$), 1.15 ± 0.08 (1 SD, $n = 12$), and 0.94 ± 0.28 (1 SD, $n = 61$), respectively. In a measurement of $^{239+240}$Pu in soil with three of the above laboratories, there was a 2.7% coefficient of variation among values reported. Corroboration of *in-situ* gamma spectrometry measurements was more difficult to determine as there was no direct intercomparison exercise conducted. However, comparison was made of external exposure-rates on the islands of Bikini Atoll derived from two independent sets of environmental measurement data: (1) ground level *in-situ* spectrometry measurements made with HPGe detectors in 1993 by the NWRS, and (2) aerial (25 m) gamma spectral measurements made with NaI detectors in 1987 by a contractor of the U.S. Department of Energy (EG&G 1982). The data were decay corrected to the same point in time. Almost without exception, islands that were very small in size had poorer agreement than larger islands. For Bikini Island, the average ratio between the two data sets was nearly 1.0. The average of all 99 values compared was 0.78; 81% of the ratios fell between 0.5 and 2.0.

In-situ gamma spectrometry measurements were made with high purity germanium detectors (HPGe) of 40% nominal efficiency (relative to a 3 in. × 3 in. NaI detector). These detectors were attached to 7 L liquid nitrogen cryostats, which could maintain suitably low temperatures in a tropical environment for over 3 d time. The minimum detectable *in-situ* count-rate for ^{137}Cs was estimated to be 0.0085 c s^{-1} for a counting time of 2 h. That count-rate corresponds approximately to 15 Bq m^{-2} of ^{137}Cs. *In-situ* detection limits for ^{241}Am and ^{60}Co were determined to be approximately 100 and 10 Bq m^{-2}, respectively.

Laboratory measurements for gamma emitters were conducted with two electro-cooled HPGe detectors of 40% efficiency with extended low-energy response. Detectors were each housed in 1-inch-thick lead shields, which were located in an air-conditioned building of wood construction. The counting facility was built on a bed of crushed coral that was dredged from the Majuro lagoon. The building was surrounded on 3 sides by the lagoon, approximately 4 m from the building, thus ensuring a low background environment. The minimum detectable concentrations for ^{241}Am, ^{137}Cs and ^{60}Co were estimated to be 2.0, 0.3, and 0.2 Bq kg^{-1}, respectively, for a 12-h counting period.

Gamma emitters, other than naturally occurring radioactivity, that were sometimes detected included ^{60}Co, ^{137}Cs, ^{152}Eu, ^{155}Eu, ^{102}Rh, ^{207}Bi and ^{241}Am. The detection of ^{152}Eu, ^{155}Eu, ^{102}Rh, and ^{207}Bi was limited to samples from the test site atolls.

Measurement of transuranic radioactivity was made by gamma spectrometry in the case of ^{241}Am and by alpha spectrometry for ^{238}Pu, ^{239}Pu, and ^{240}Pu. Plutonium extraction was based on the method of leaching, extraction with an ion exchange column followed by microprecipitation onto neodymium fluoride mounting. Minimum detectable concentration for plutonium isotopes was not explicitly calculated because in our procedure the sample mass was adjusted, based on a prior gamma spectrometry measurement of the ^{241}Am, to maintain approximately equal counting times necessary to maintain a measurement precision of ± 10% at 1 sigma confidence level. The minimum detectable concentration was empirically observed to be on the order of 0.04 Bq kg^{-1} for a 12-h counting period.

Measurement of ^{90}Sr/^{90}Y in soils and plants is also of interest for purposes of determining contamination by regional fallout and for assessing doses; however, these radionuclides were not measured by the NWRS for two reasons. First, resource limitations prevented incorporating measurements of strontium into the laboratory program. Second, previous measurement programs of food crops (e.g., Robison et al. 1988) showed that the concentration of ^{90}Sr in coconut milk was over 500 × less than for ^{137}Cs. Consequently, strontium normally contributes only 5–10% of the total projected dose.

Dosimetric evaluation

The radiological measurement data were used to estimate the expected effective dose-rate in 1994 using an assumed set of lifestyle and dietary assumptions. Methodology used for estimating prospective doses is discussed in Simon and Graham (1996) using a dietary model reported by Dignan et al. (1994) and external and internal dose factors from ICRP (1987; 1989).

For calculations of external exposure, building shielding was incorporated based on the assumptions of 9 h per day indoors and the combination of house building materials (wood) plus a coral gravel layer spread around the house reduces the exposure-rate from ^{137}Cs by 50%. The value used for effective dose equivalent per unit exposure from ^{137}Cs was 0.00613 Sv R^{-1}, interpolated from data in ICRP (1987). Age-dependent dose factors for internal dose were used for an assessment to the Rongelap population (Simon 1995); in all other cases, adult dose factors were used.

The dietary assumptions are an important determinant to the magnitude of estimated doses. The dietary data reported by Dignan et al. (1994) indicated that locally grown food contributed about 18% of the total caloric intake for the Rongelap community presently residing on a small island in Kwajalein Atoll. Total caloric intake-rates were estimated to be 1,900 ± 100 (1 SE, n = 48) and 2,750 ± 146 (1 SE, n = 68) kcal d^{-1} for women and men, respectively. The residence of the Rongelap people in Kwajalein Atoll, however, is temporary until resettlement of Rongelap Atoll can take place. Because this group of people is receiving surplus USDA food and financial compensation, their diet is minimally applicable to other Marshallese communities.

The dietary model for the internal dose calculations reported here assumes that 75% of the dietary intake is from a mixture of locally grown food, the remainder being imported rice. The relative proportions of locally grown food were extrapolated from the diet of Dignan. It is acknowledged that few Marshallese eat a diet containing this high of a proportion of locally produced food; however, this diet describes a traditional lifestyle diet (including rice), which may be chosen by some Marshallese. Regardless of the likelihood that individuals will consume such a diet in the future, the calculations presented here provide useful information to members of the community who are considering resettlement of Rongelap. Doses from other proportions of local food can be easily estimated by scaling the findings presented here.

Assessment calculations explicitly used radiological measurement data from the atoll surveys or parameter values estimated from the data. Soil concentrations of ^{137}Cs were estimated from the *in-situ* gamma spectrometric measurements by averaging the area inventory over the approximate root zone depth (30 cm). Those data were combined either with empirical data on concentrations in food or used with plant:soil concentration factors determined during the course of this study or reported by other investigators (e.g., Robison et al. 1982) to predict radioactivity levels in food and the subsequent intake.

RESULTS AND DISCUSSION

The findings of the NWRS are presented here in the same general form as presented to the Marshall Islands Government (Simon and Graham 1995a,b,c,d,e) though space limitations prohibit presenting findings of all radionuclides for all locations and for all of the various food products. The complete set of soil measurement data is shown for the purpose of indicating the range of data as well as the distribution of values. The data, shown in graphical form, are presented by island from which the samples were obtained. This presentation design best supports the needs of the Marshallese since their traditional lifestyle is to build the main community on the largest island and to use smaller islands of the atoll for food gathering purposes.

Previous reports (e.g., Robison et al. 1982; Robison and Phillips 1989) have shown that ^{137}Cs easily contributes most of the external and internal dose to present and future inhabitants of the atolls. This premise was examined both by measurement and computation and appears to be a valid conclusion. Hence, the findings presented here emphasize ^{137}Cs. Measurements of transuranic radioactivity were also made for completeness and because of public interest though calculations show that the dose commitment is small under any but extremely unusual circumstances. The importance of plutonium measurements may lie more within the realm of public perception of risk. The graphs of plutonium measurement data that are presented here also indicate the range and distribution as well as spatial variation among islands.

The *in-situ* gamma spectrometric measurement data were used to produce estimates of external exposure-rate from the primary gamma emitting radionuclides still present in the terrestrial environment, including ^{137}Cs, ^{241}Am and ^{60}Co. Because of the low environmental levels of ^{60}Co and the low penetrating power of ^{241}Am photons, only ^{137}Cs contributes significantly to the exposure-rate and, hence, to the external dose. Only the exposure-rate due to ^{137}Cs in the soil is reported here because the addition of the exposure-rate from ^{241}Am and ^{60}Co increases the exposure-rate by less than a few percent, well within the possible error of the ^{137}Cs dose estimates.

Fig. 1 shows the data set of areal activities (Bq m^{-2} ^{137}Cs) estimated from *in-situ* gamma spectrometry measurements. The atolls are ordered from left to right in this figure by the maximum value observed at each atoll. The atolls of Kwajalein, Rongelap, and Enewetak are divided into north (N) and south (S) sections either because of the extraordinarily large size of the atoll (Kwajalein) or because of a significant south to north contamination gradient over the atoll. The areal activity values, as well

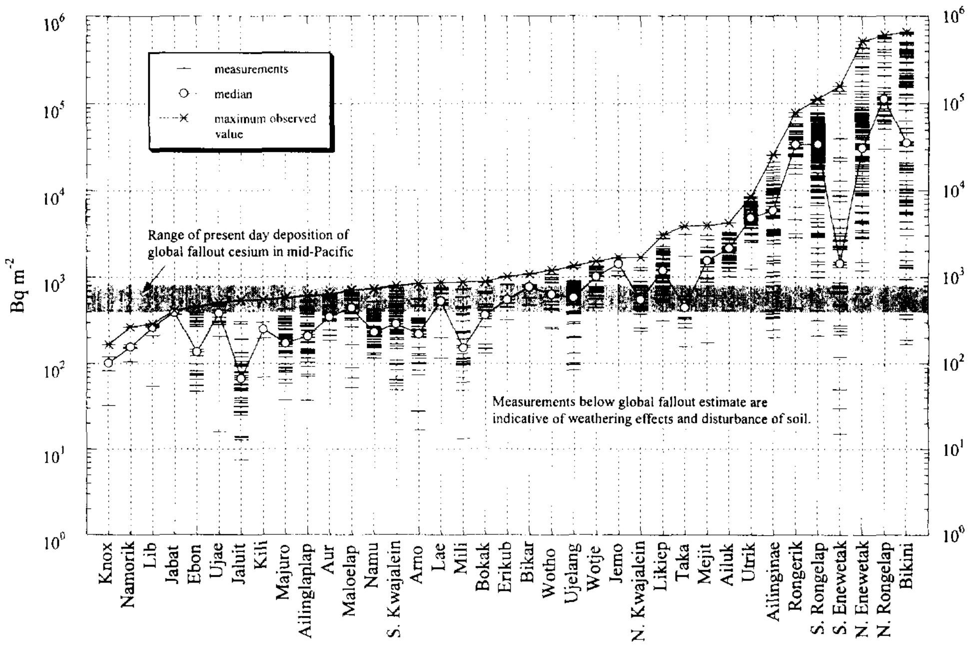

Fig. 1. Areal inventories of ^{137}Cs (Bq m^{-2}) at all atolls as estimated from *in-situ* gamma spectrometry measurements, ordered left to right by maximum observed value at each atoll (Kwajalein, Rongelap and Enewetak are divided into south and north portions).

as the external effective dose-rates, span five orders of magnitude. The data for about 10 atolls are not significantly different from the mean expected value of global fallout ^{137}Cs today at mid-Pacific latitudes.

Estimates of global fallout in the mid-Pacific were obtained from published data (Harley et al. 1960; Larsen 1985) and decay corrected to 1994. Data of ^{90}Sr deposition were used to derive cesium estimates by assuming a production ratio of ^{137}Cs/^{90}Sr of 1.6. The data on global fallout have been examined with respect to latitudinal and precipitation variation. Generally, global fallout deposition increases with increasing latitude in the northern hemisphere though it is also a strong function of annual precipitation rate. Within the Marshall Islands archipelago, a strong north-south rainfall gradient exists with annual precipitation of 300 cm typical in the southern atolls and 100 cm in the northern atolls. Thus, the possibility of higher deposition in the northern atolls was likely offset by the lower rainfall there. We believe the expected contribution from global fallout across the atolls of the Marshall Islands to be relatively constant because of this opposing effect and is estimated to be presently between 400 and 800 Bq m^{-2} of ^{137}Cs.

The activity ratio of ^{137}Cs to $^{239+240}$Pu from global fallout was investigated in the early 1970's by the AEC Health and Safety Laboratory (HASL) and determined to be a constant value in the north temperate zone. Based on further data collected by the HASL in 1979, the best estimate of the ratio in 1979 was determined to be 53 ± 0.5 (1 SD) (Beck and Krey 1983). Decay correcting this value to 1993, the mean date of the RMI measurements, would give a ratio of cesium to plutonium of 38.4 ± 0.36. Thus, the best estimate for plutonium in the environment of the Marshall Islands from global fallout is between 11 and 22 Bq m^{-2}. Assuming unit density for the top 5 cm of soil and a uniform distribution within this layer, the contribution of plutonium from global fallout is estimated to be between 0.2 and 0.4 Bq kg^{-1}. Different units have been used to describe the global contributions for cesium and plutonium because plutonium has not migrated downward to any significant degree and is almost entirely resident in the top 5 cm except where the soil has been overturned by natural events, animals or humans.

The external exposure-rates in only a very few locations, e.g., the northern islands of Enewetak, Rongelap and Bikini Atoll, would be considered to be at levels inappropriate for public residence (several mSv y^{-1}). These locations correspond to areal inventories greater than 10^5 Bq m^{-2}. There are a greater number of locations where careful consideration needs to be given to the interpretation and advice offered to Marshallese concerning radioactive contamination of food crops. The mobility of ^{137}Cs into plants via root uptake is enhanced in the coral soil environment relative to most continental locations because of the absence of clay minerals and the very low levels of potassium in the soil. Thus, in some locations on the atolls of Enewetak, Bikini and Rongelap, concentrations of ^{137}Cs in important food crops may be higher than 1,000 Bq kg^{-1} by up to a factor of 10× or 20×.

There is little international guidance available to suggest limits on radioactivity in foods except for the purpose of limiting international commerce of contaminated foods as set by the Codex Alimentarius Commission (WHO 1988; FAO 1991) of the Food and Agriculture Organization of the United Nations (FAO) and World Health Organization (WHO). Similar levels were recommended by the International Atomic Energy Agency (IAEA 1994) as a generic intervention level to be applied following the accidental release of radionuclides for the specific case where alternative food supplies are readily available. Neither of these situations, however, are exactly applicable to previously contaminated lands. Because coconut milk and coconut meat are so important to the traditional Marshallese diet, and the fluid in some cases is the main source of liquid replenishment, careful evaluation is required concerning any recommendations to limit the use of local foods. The Codex limit of 1,000 Bq kg^{-1} has been useful, however, for judging the severity of contamination. Recommendations have been given to the Marshallese that lands should be remediated if they are contaminated to a degree such that food concentrations result significantly in excess of the Codex recommendations. Remediation for ^{137}Cs may be accomplished most easily by soil amendments of potassium (Robison and Stone 1992).

At each atoll, a range of soil cesium values or exposure-rates was observed (see Table 1). Ratios of the observed maximum to minimum values were usually less than a range of 50 (80% of atolls) though many were closer to a range of 25 (70% of atolls) and the median range was 10. This range of values is considered to be the result of both variations in the original deposition over the atoll as well as the result of weathering effects (downward migration, erosion) and human or animal disturbance to the soil.

Some indication of historical soil disturbance was evident by the percentage of deep soil profiles (0–30 cm) that deviated from the negative exponential model. Nearly half of 202 profiles sampled from the entirety of the Marshall Islands did not strictly fit a negative exponential model as indicated by a regression coefficient of determination (r^2) $\leq$ 90% (Graham and Simon 1996), though only a few deviated severely. Profiles showing extreme evidence of disturbance were generally limited to very small, erosion prone islands. Such deviations lead to increased uncertainty in calculations of soil inventory and exposure-rate; however, locations where there was evidence of previous soil movement or construction activities were generally avoided for making measurements. The range of data was not exaggerated by using sites expected to be unusually low; sample sites were chosen to avoid beach or highly eroded areas. Only five atolls had an observed maximum to minimum ratio for soil cesium that exceeded 100: Ailinginae, Rongerik, Rongelap, Bikini and Enewetak.

Other summary information of the measurement program is provided in Table 1. Included in this table is the number of islands monitored from each atoll, the number of soil profiles per km^2 in each atoll, the number of *in-situ* gamma spectrometry measurements per km^2 in each atoll and the number of *in-situ* measurements per soil profile. Generally, higher values for the three latter variables were indicative of small, separate reef islands (e.g., Jemo, Lib, etc.) or atolls of greater public interest.

For purposes of communicating with the public on the issue of relative contamination of the atolls, each atoll was ranked according to the relative degree that its deposition exceeded that from global fallout (Table 1). Four atolls (12%) had soil cesium levels not different from the mean expected global fallout level. Another nine atolls (22%) were possibly not different or only slightly above the mean global deposition. Seven atolls (21%) exceed the mean global fallout level by more than 10 times and 4 atolls (12%) exceeded it by more than 100 times.

A distinct pattern of increasing soil inventory with increasing latitude was observed. This pattern was generally expected due to the location of the test sites in the northern part of the nation and because the normal direction of the tradewinds is roughly along lines of constant latitude. Fig. 2 shows the maximum value of areal inventory of ^{137}Cs (Bq m^{-2}) from each atoll plotted as a function of latitude.

The maximum value of deposition at each atoll can be interpreted to be closest to the original value of deposition at each atoll after accounting for radioactive decay. This is most likely a good assumption for atolls that lie at distances of 100 km or more from the test sites though it is less certain for the test sites or nearby atolls. All islands in the Marshall Islands are coral and are virtually flat with highly porous soil with the result that precipitation is quickly absorbed into the soil. Standing water following storms is very rare; furthermore, there is no apparent erosion from runoff that might lead to collection of radioactivity in localized areas. The weathering process, in general, decreases the radioactivity inventory in the upper soil horizons over whole islands and does not result in localized variations. Regardless of the soundness of these hypotheses, the strong gradient in areal inventory with changes in latitude was clearly observed. Atolls at latitudes greater than 9° N show some evidence of having received local fallout deposition.

The predicted external plus internal effective dose-rate from ^{137}Cs ordered by atoll median for the diet of 75% locally grown food is shown in Fig. 3. The range of uncertainty (95% confidence interval) was determined to be approximately a multiplicative factor of 2.5 in either direction. This range was determined from stochastic calculations discussed in detail in Simon (1995) and in brief in Simon and Graham (1996). The calculations account for the variability of caloric intake among individuals, plant:soil concentration ratios and the range of soil concentrations typically encountered in a single atoll environment. In these calculations, however, the proportion of local food is set to be a constant value because various scenarios for the proportion of local food were examined separately.

Detailed data are presented in this paper for the islands of the test site atolls Bikini and Enewetak as well

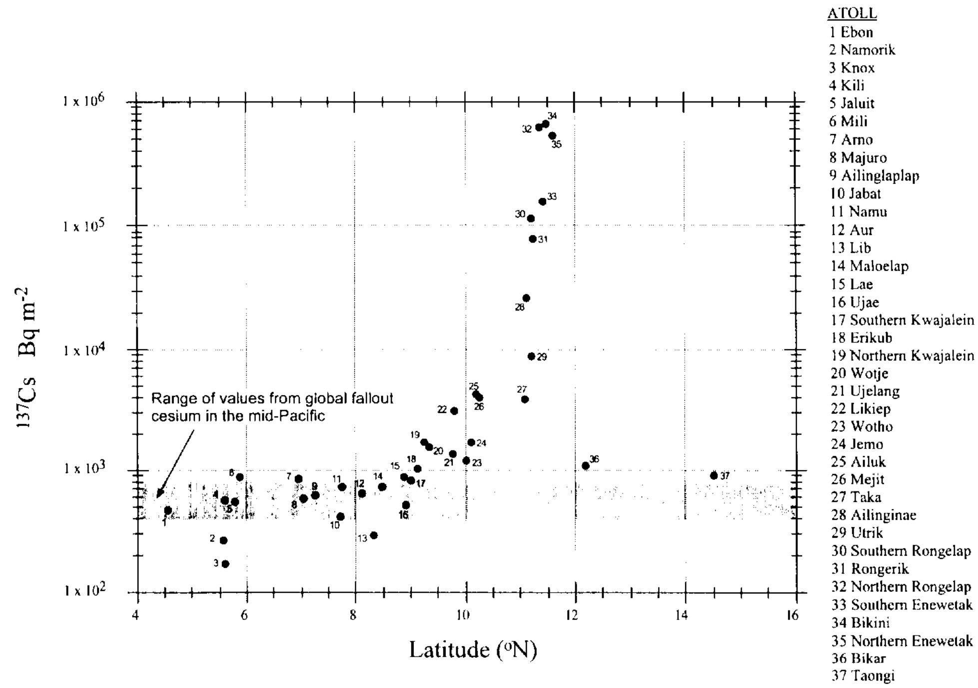

Fig. 2. Maximum observed value of ^{137}Cs in soil of atolls of the Marshall Islands (Bq m^{-2}) as a function of latitude (Kwajalein, Rongelap and Enewetak are divided into south and north portions).

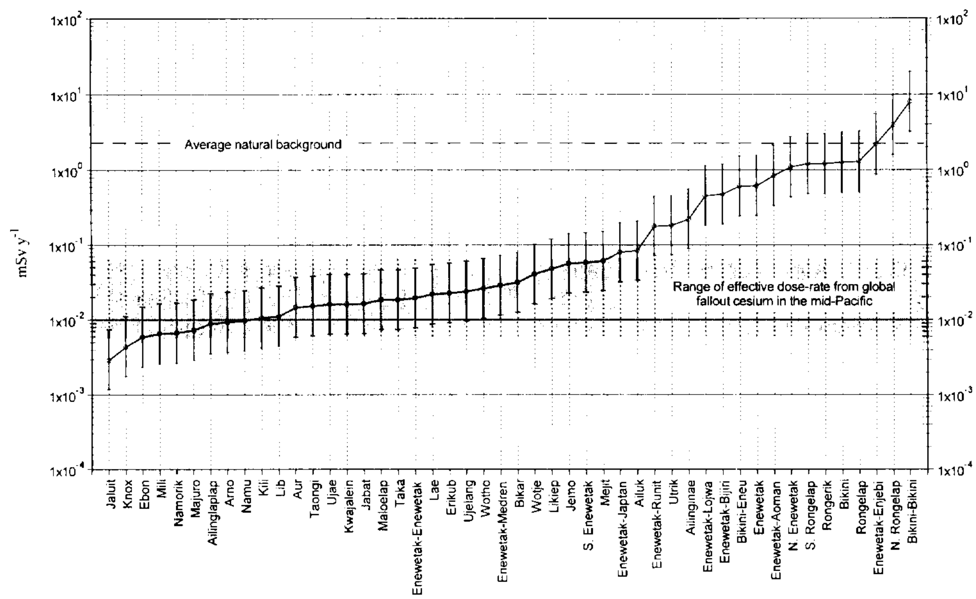

Fig. 3. All atolls: median predicted external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

as the islands of the other northern atolls within or near to the centerline of the fallout trajectory of the BRAVO event (see DNA 1979 for four similar cloud trajectory projections). Those atolls include Rongelap, Rongerik, Ailinginae, and Utrik. The remaining figures in this section present data for individual islands within these atolls. Three figures are shown for each of the atolls listed above: external effective dose-rate (mSv y^{-1}) from ^{137}Cs, external plus internal dose-rate from ^{137}Cs for the 75% local food diet (mSv y^{-1}), and measurements of ^{239,240}Pu in soil (Bq kg^{-1}). Figs. 4 through 6 are for Enewetak Atoll, Figs. 7 through 9 are for Bikini Atoll, Figs. 10 through 12 are for Rongelap Atoll, Figs. 13 through 15 are for Ailinginae Atoll, Figs. 16 through 18

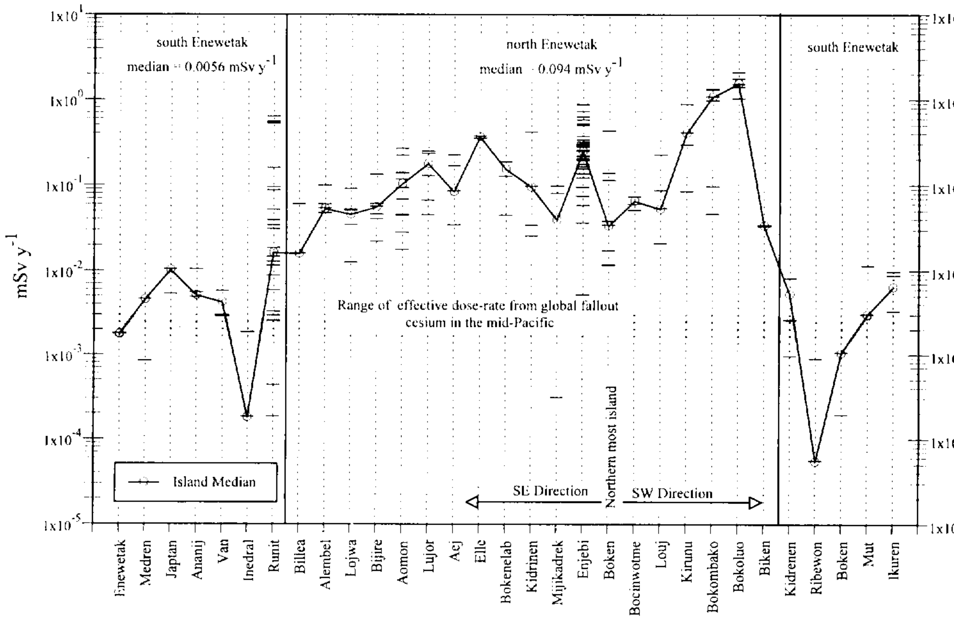

Fig. 4. Islands of Enewetak Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

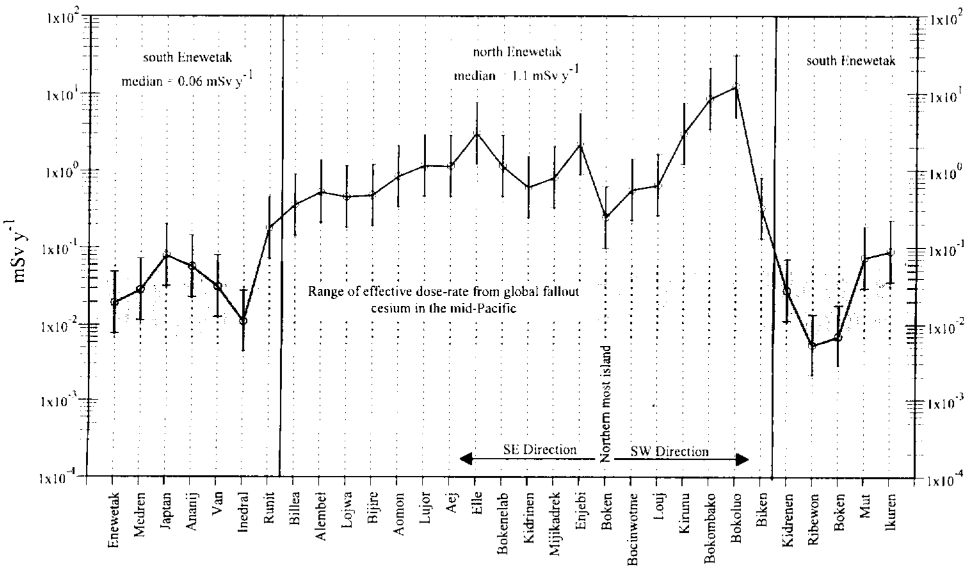

Fig. 5. Islands of Enewetak Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

are for Rongerik Atoll, and Figs. 19 through 21 are for Utrik Atoll.

For each figure, there are two reference values useful for comparison purposes: the level of radioactivity resulting from global fallout and the average background radiation dose to typical Marshallese. For those figures showing only external dose-rate (Figs. 4, 7, 10, 13, 16, 19), a useful comparison is the external effective dose-rate from global fallout cesium. This value (gray band) is based on our estimate of 400–800 Bq m^{-2} deposition of ^{137}Cs in the mid-Pacific. Our calculated dose-rates for this case are between 1.5×10^{-3} and 3×10^{-3} mSv y^{-1}. For those figures showing external plus internal dose-rate (Figs. 3, 5, 8, 11, 14, 17, 20), a useful comparison is the external plus internal dose-rate from global fallout cesium and based on a diet of 75% locally produced food. The range of possible dose-rates in this case is wider than for the external dose-rate by a factor of 2.5× to account for the additional uncertainties in food-chain transport and in dietary assumptions. Our calculated dose-rates for

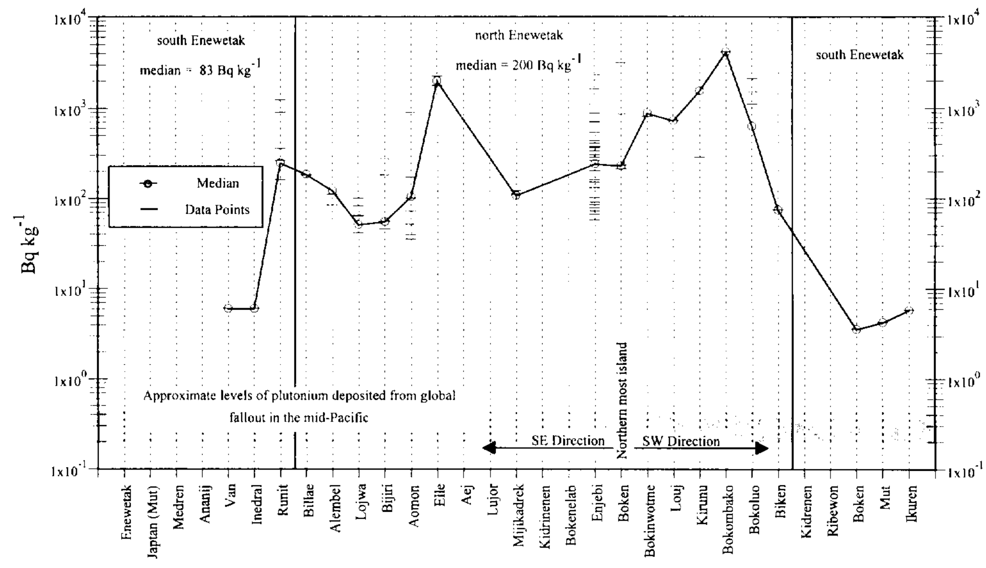

Fig. 6. Islands of Enewetak Atoll: surface soil (0–5 cm) concentrations of ^{239,240}Pu (Bq kg^{-1}).

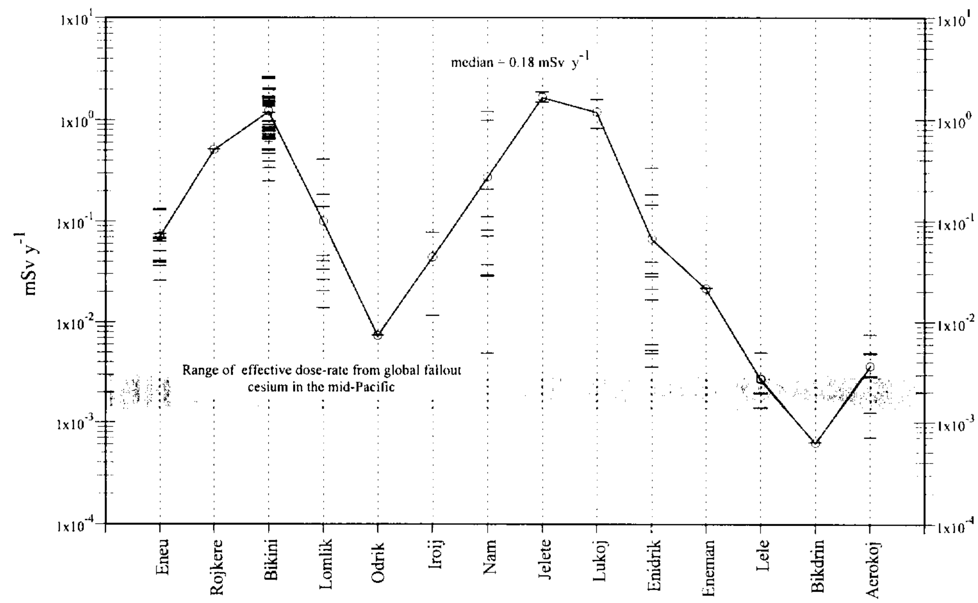

Fig. 7. Islands of Bikini Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

this case are between 5.6×10^{-3} and 6.75×10^{-2} mSv y^{-1}. For those figures showing surface soil concentrations of $^{239+240}$Pu (see Figs. 6, 9, 12, 15, 18, 21), a useful comparison is the concentration of plutonium expected in the soil from global fallout. Our estimated concentrations range from 0.21 to 0.42 Bq kg^{-1}. That range of values was derived from the ratio of cesium:plutonium discussed earlier and the deposition of cesium expected from global fallout.

An additional reference value useful for developing a perspective of the dose-rates shown here is the average background radiation dose received by typical Marshallese. It has been known for decades that natural radioactivity in the terrestrial environment is much lower in coral soils than in volcanic soils and the contribution of cosmic rays is lower at locations close to sea level. Thus, without dietary sources of radiation, the background dose in the Marshall Islands would be much lower (approximately 0.24 mSv y^{-1} for the sum of terrestrial and cosmic radiation) than at continental locations. However, because the typical diet of the indigenous people of the Marshall Islands depends greatly on seafood, the back-

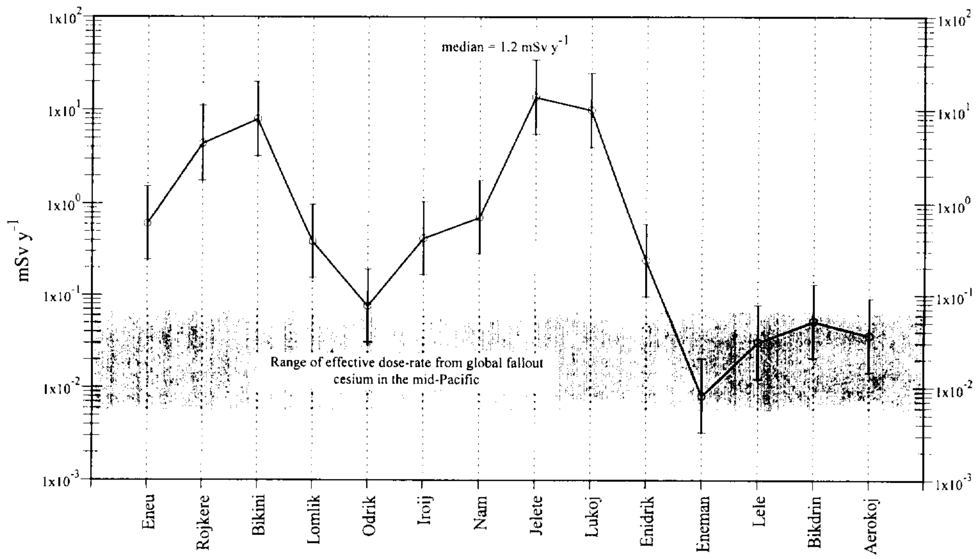

Fig. 8. Islands of Bikini Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

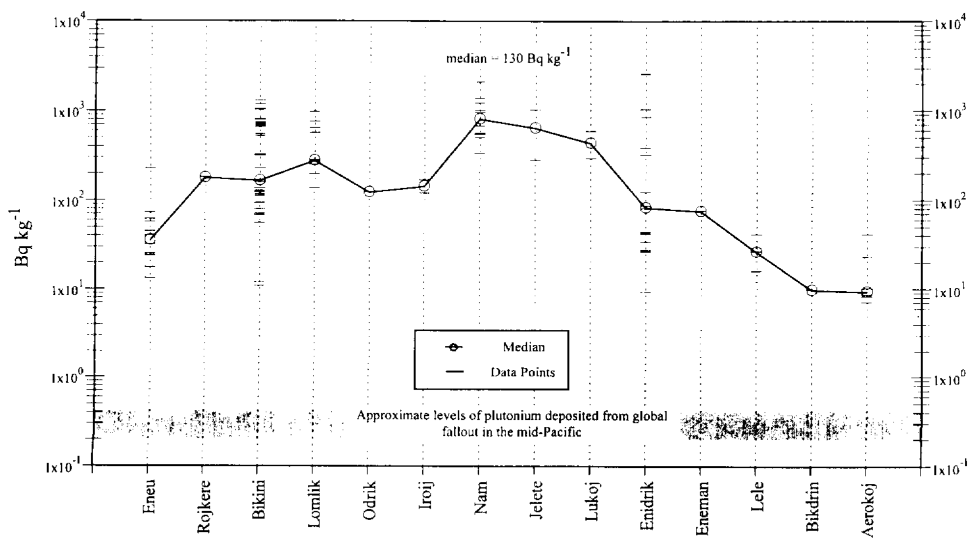

Fig. 9. Islands of Bikini Atoll: surface soil (0–5 cm) concentrations of $^{239,240}Pu$ (Bq kg^{-1}).

ground radiation dose is substantially increased due to ingestion contributions of ^{210}Po and ^{210}Pb in fish. The total average background radiation dose to Marshallese was reported by Noshkin et al. (1994) to be approximately 2.4 mSv, not much different than experienced elsewhere. However, as discussed, the primary source of that radiation dose is dietary rather than from radon and terrestrial gamma rays.

Two general trends in the measurement data were observed: (1) Terrestrial soil contamination levels at atolls other than the test site atolls generally do not vary by more than a factor of 50 among the islands of a single atoll, variations of a factor of 25 are more common; and (2) Small islands (i.e., less than 500 m length or 100 m width) invariably display lower concentrations of radioactivity in soil than do larger islands within the same atoll. Presumably smaller islands are more susceptible to erosion and washover by storm waves as well as to changes in the shape and mass of the island from deposition of new coral sand during tidal changes and storms. Furthermore, smaller islands have less developed vegetation, less litter; small islands also have poorly

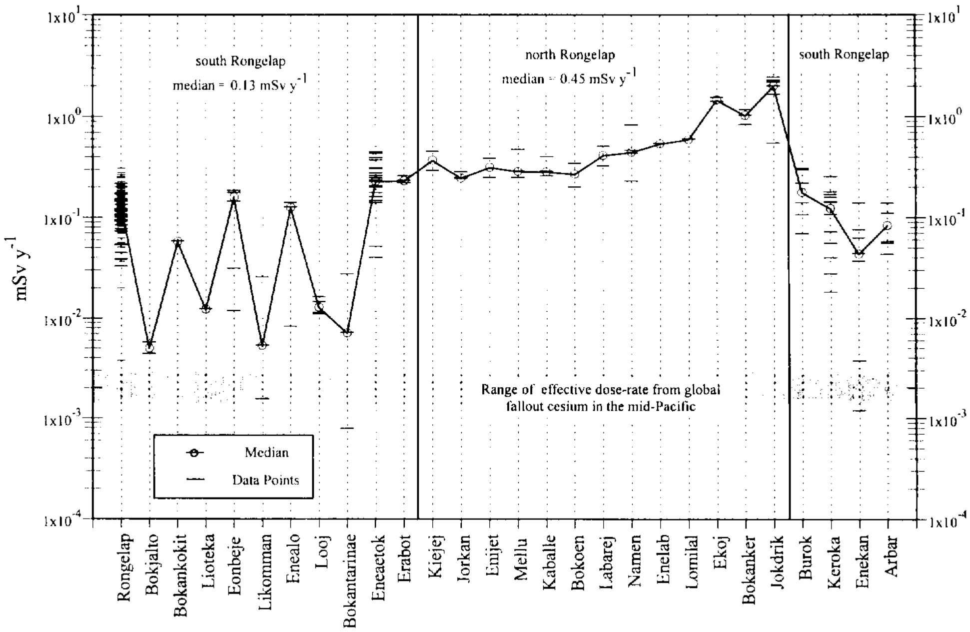

Fig. 10. Islands of Rongelap Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

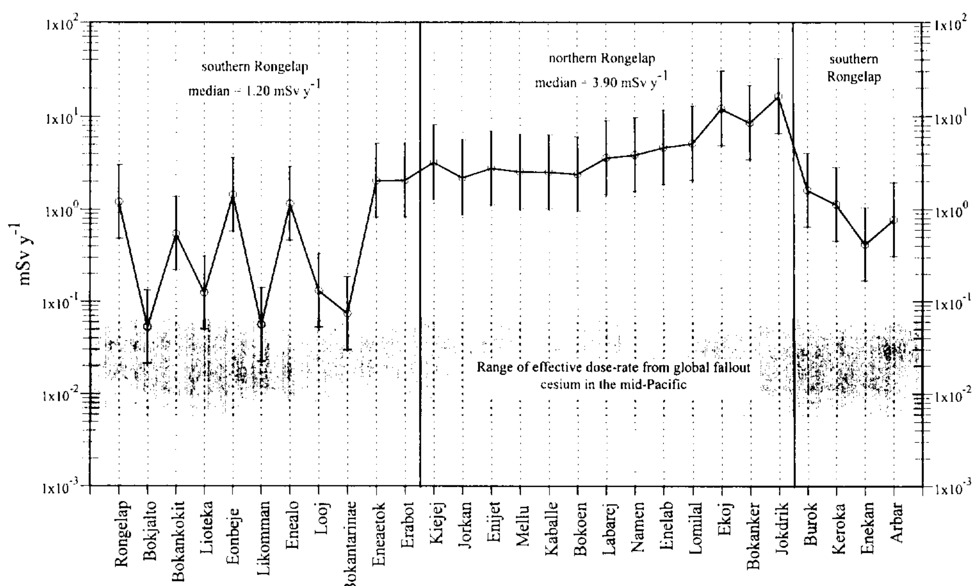

Fig. 11. Islands of Rongelap Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

developed soil with which to bind radioactivity deposited there.

SUMMARY

The NWRS has documented for the first time the present day levels of residual weapons fallout radioactivity throughout the entirety of the Marshall Islands. Radionuclide specific activities in the soil of islands in the mid-Pacific from global fallout sources are estimated from the literature to be approximately 400 to 800 Bq m^{-2} for ^{137}Cs and 0.2 to 0.4 Bq kg^{-1} for $^{239,240}Pu$. Based on our observations, there are four atolls that show no evidence of having received local fallout from the

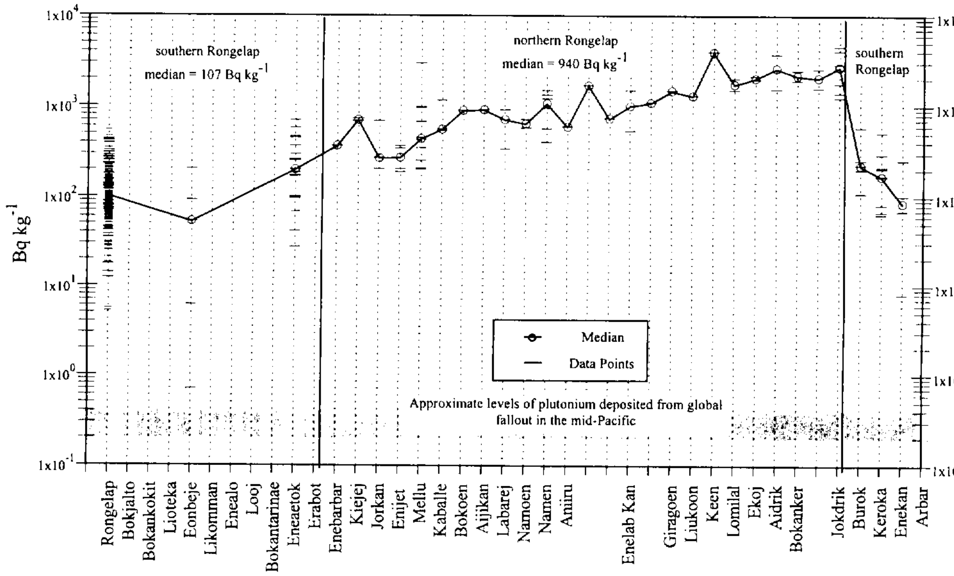

Fig. 12. Islands of Rongelap Atoll: surface soil (0–5 cm) concentrations of $^{239,240}Pu$ (Bq kg^{-1}) (unidentified locations are small unnamed islets).

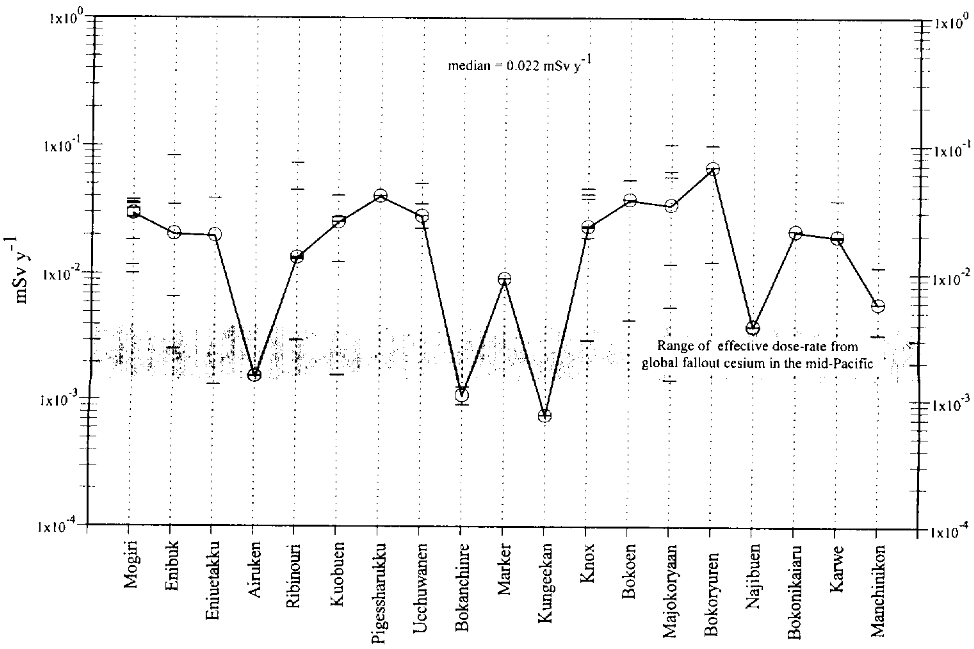

Fig. 13. Islands of Ailinginae Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

tests at Bikini and Enewetak. There are another ten atolls for which we cannot conclusively determine whether or not they received any local fallout or whether they are above the expected global background value.

Though most of the southern atolls in the RMI are near the expected global background level, some measurements were below this. Explanations for this phenomenon include weathering effects resulting in downward migration, dilution with clean humic material by litter fall or with coral material brought up from deep soil horizons by human or animal disturbance, erosion from ocean waves or coverage of the surface with new material from tides and waves.

A quantitative evaluation of the increase of fallout radioactivity with an increase in latitude has been documented for the first time. Specific activities in soil remain nearly constant over the latitude range of 4° N to 9° N. Values of ^{137}Cs in the terrestrial environment at locations

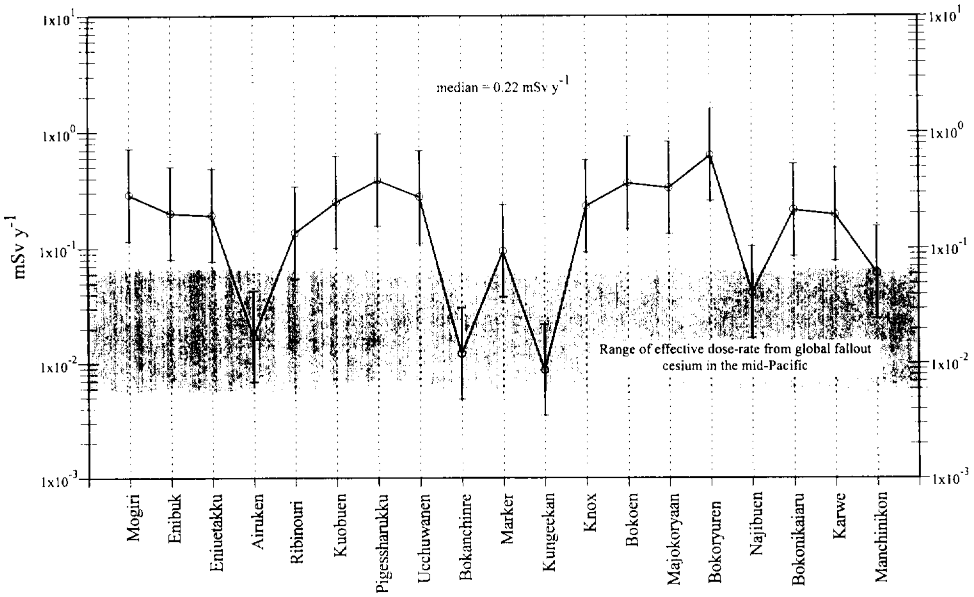

Fig. 14. Islands of Ailinginae Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

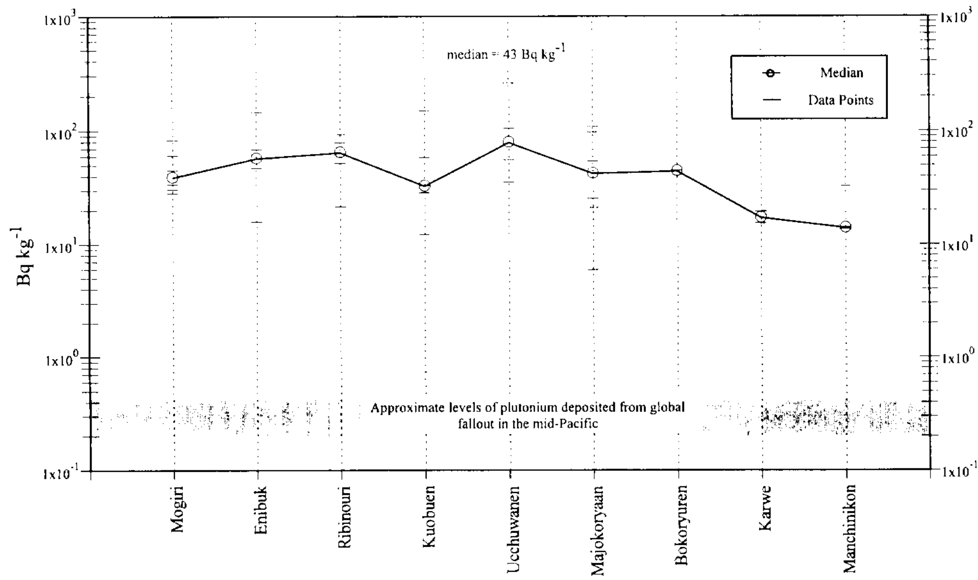

Fig. 15. Islands of Ailinginae Atoll: surface soil (0–5 cm) concentrations of $^{239,240}Pu$ (Bq kg^{-1}).

north of 9° increase rapidly to a latitude of 11.5° N where Bikini is located. At locations on three atolls, soil ^{137}Cs is more than 1,000 times the global background level.

It is apparent from our measurements that relatively small amounts of fallout reached locations as far south as Kwajalein Atoll. This conclusion corroborates the data of the HASL gummed film station which reported detectable radioactivity during the entire CASTLE and HARDTACK II series of tests conducted from 1954 through 1958.

The small amounts of residual radioactivity at the mid-latitude atolls (9° to 10.5° N) do not pose any measurable health hazard today or in the future. A number of islands in the atolls of Enewetak, Bikini and Rongelap require limited remediation before communities should be encouraged to return and live traditional lifestyles. This recommendation is contingent on the reasonable assumption that Marshallese will continue to consume locally grown food.

During its operational period, the NWRS received continuous oversight and peer review through the activities of the Scientific Advisory Panel. The laboratory of the NWRS successfully participated in international intercomparison exercises as part of a quality control

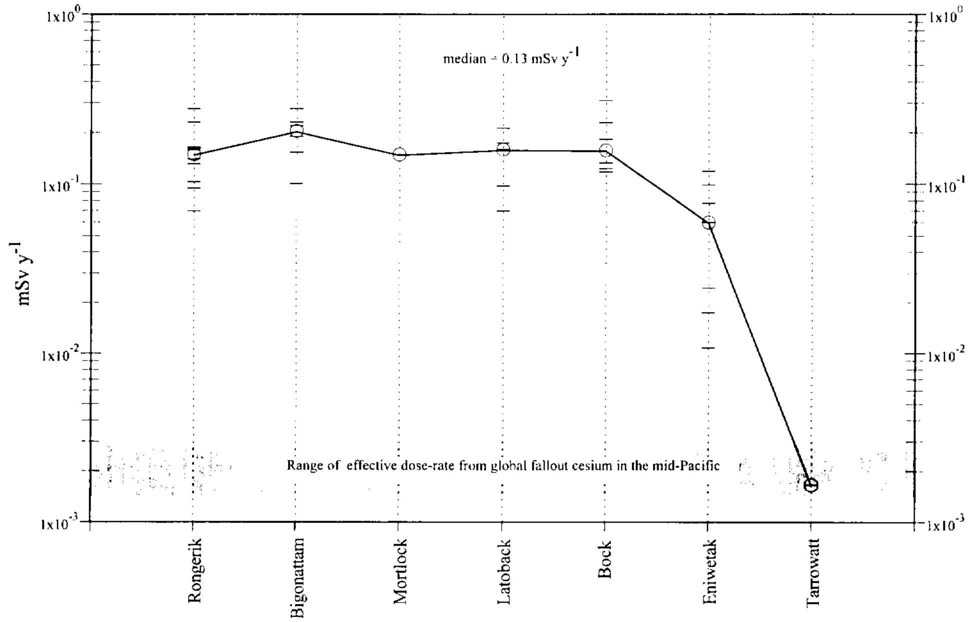

Fig. 16. Islands of Rongerik Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

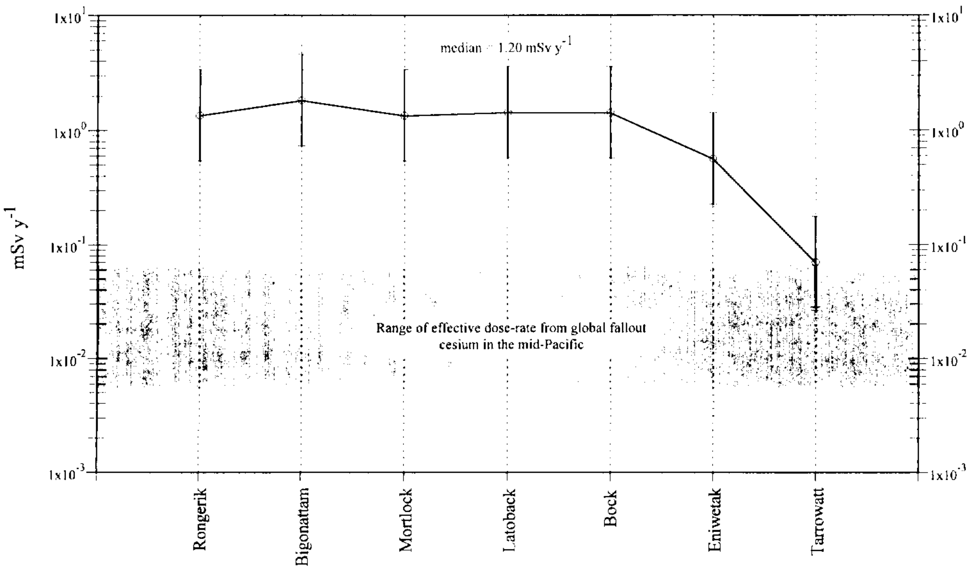

Fig. 17. Islands of Rongerik Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

program. Findings for locations previously monitored by the DOE were in good agreement. An assessment by the NWRS of the projected doses that might be received at Rongelap Atoll was similar both to findings of a National Academy of Sciences review group (NRC 1994) and to those of LLNL (Robison et al. 1994). Similarly, the findings of the NWRS for Bikini Atoll were reviewed and endorsed by an expert advisory group assembled by the International Atomic Energy Agency in December 1995 (IAEA 1996). These various activities have served to confirm the precision of the measurements and assessments reported by the NWRS.

Public perception of the dangers of residual radioactivity has been compounded among Marshallese as a result of continuing publicity over the last 40+ y, both by the popular media and by scientists. It is our observation that significant misunderstanding has been generated by the ongoing process of scientific study. Even the process of sampling foods or providing health examinations tends to add credence to local convictions of extensive radioactive contamination and latent health damage.

Adequate data on the radiological conditions of the Marshall Islands now exists such that the RMI government or local atoll authorities may determine the suit-

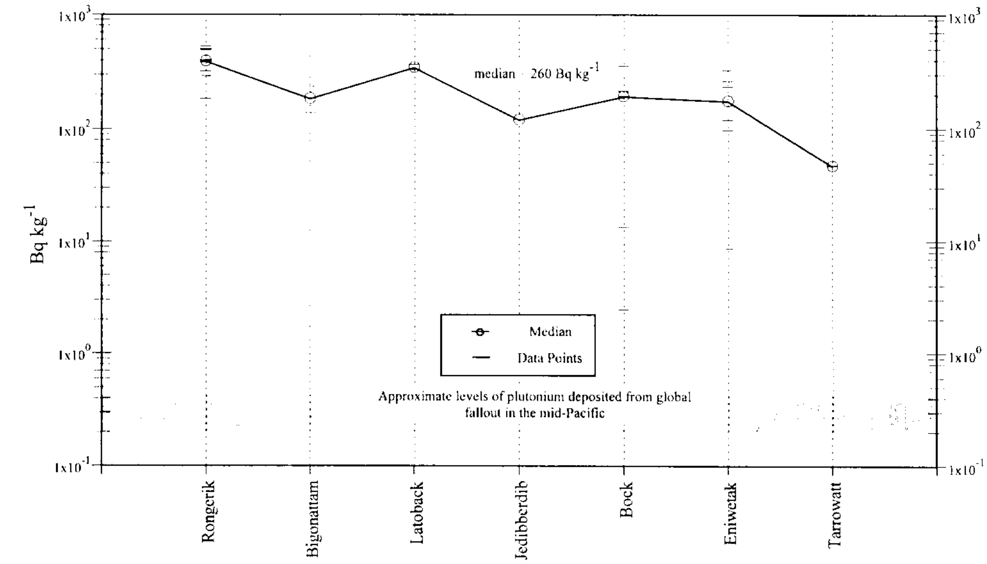

Fig. 18. Islands of Rongerik Atoll: surface soil (0–5 cm) concentrations of ^{239,240}Pu (Bq kg^{-1}).

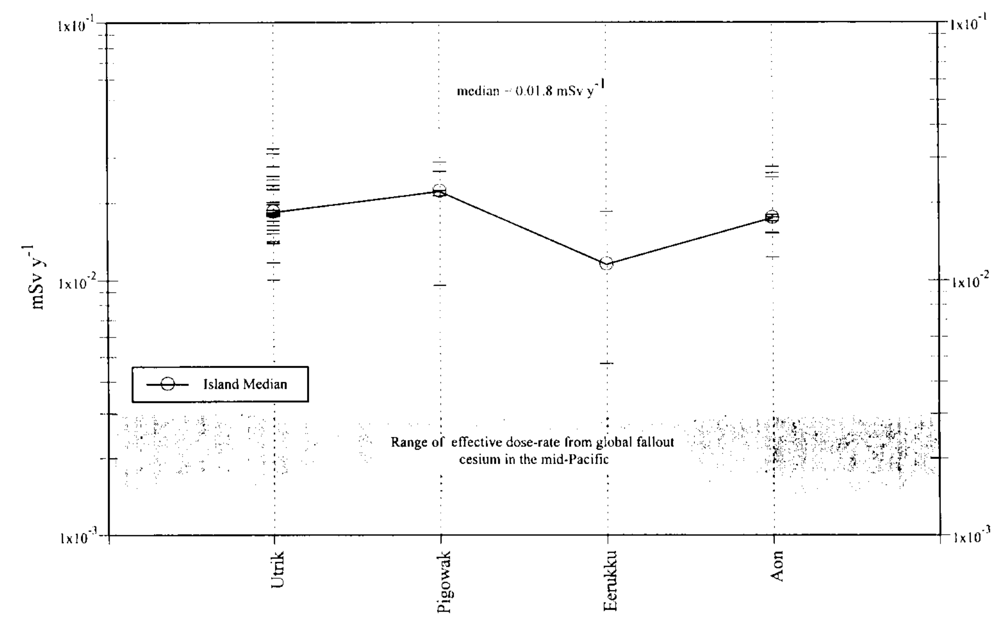

Fig. 19. Islands of Utrik Atoll: external effective dose-rate from ^{137}Cs (mSv y^{-1}).

ability of any location for habitation and food gathering. The main challenge with respect to the radiological conditions of the Marshall Islands, other than remediation of limited locations, is in increasing the understanding of government leaders, health care workers, teachers, the media and the public about the true risks of radioactivity and about natural causes for cancer and other common diseases which, only in some instances, may be radiogenic in origin.

Acknowledgments—The Government of the Republic of the Marshall Islands provided financial support to the Nationwide Radiological Study. Administrative support was provided by the Office of the Chief Secretary and the Ministry of Foreign Affairs; liaison support was provided by Peter Oliver. Andrew Barron and Susan Duffy were an integral part of the original field survey team. Shiela Como and Andy Borchert served as laboratory radiochemists. Numerous Marshallese provided important assistance to the field and laboratory program, including Helkenna Anni, Antonio Jackson, Alee Jonas, Randy Thomas, Tom Schmit, Rosen Jorbwij, Ransey Larron, Glasses Mokroro, Alexander Noah, Renny Ohwiler, Fred Opet. Dirk H. R. Spenneman provided background information documents to support several of the atoll surveys. The Scientific Advisory Panel [A. C. McEwan (Chairman), K. F. Baverstock, H. G. Paretzke, K. Sankaranarayanan and K. R. Trott] were eminently helpful in designing and guiding the study and personally provided assistance on a wide range of technical issues and activities. Merril Eisenbud provided a great deal of direction to the principal scientist in matters of acquiring historical data and in setting

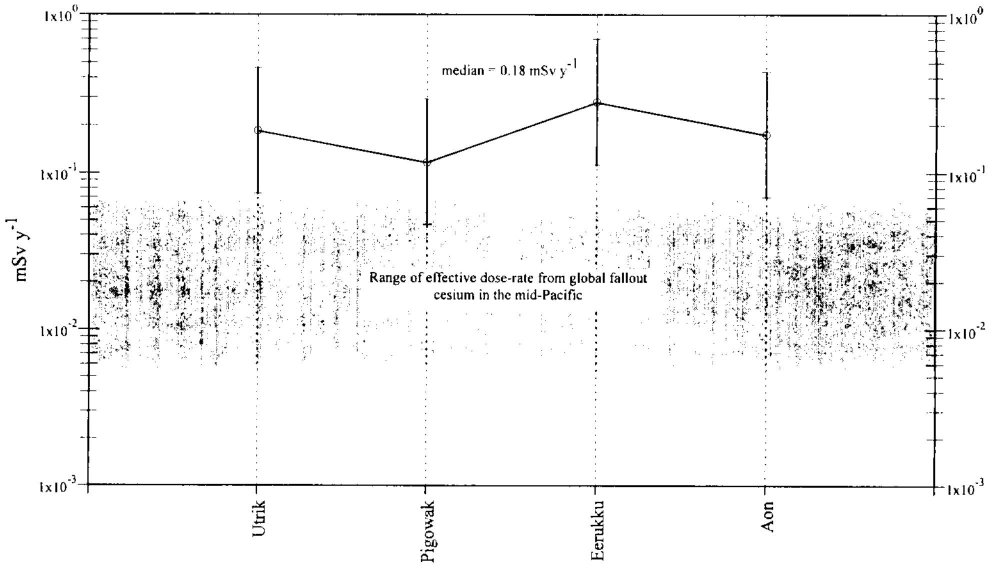

Fig. 20. Islands of Utrik Atoll: external (including building shielding) plus internal effective dose-rate from ^{137}Cs assuming a diet of 75% locally grown food (mSv y^{-1}).

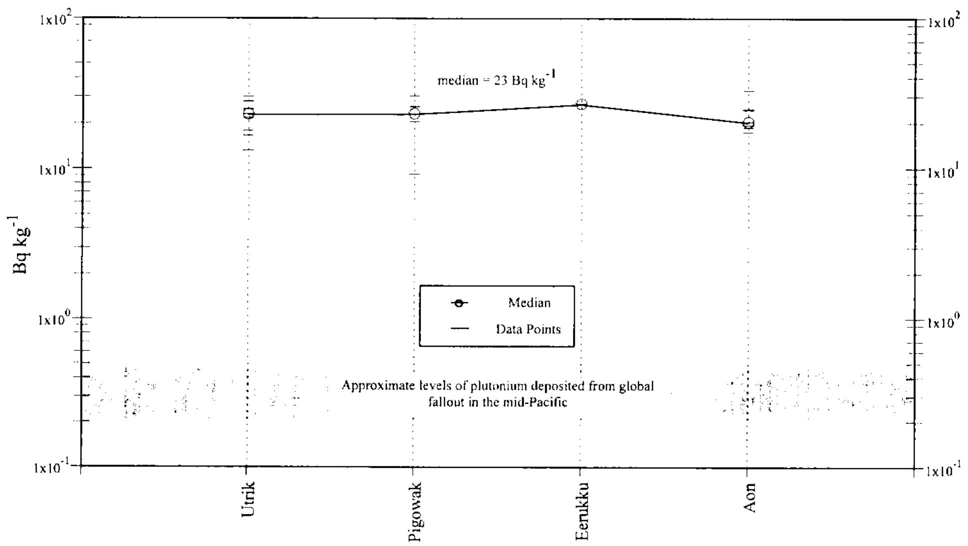

Fig. 21. Islands of Utrik Atoll: surface soil (0–5 cm) concentrations of $^{239,240}Pu$ (Bq kg^{-1}).

an example of how to conduct a study with scientific integrity. Staff of the U.S. Department of Energy and its contractor laboratories were helpful on many occasions, in particular, William Robison, Casper Sun, Harry Pettingill and Tom Bell. A number of individuals including the late Jeton Anjain, the late Henry Kohn, Harold Beck, Shawki Ibrahim and others contributed various kinds of support, advice or technical guidance. We thank the communities and local governments of the Marshall Islands for their cooperation and assistance during the intrusion into their lives by our atoll surveys. Rita Escher provided editorial comments on a draft of this manuscript. Finally, we thank our families and the families of the other staff who endured the long study with great patience.

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